TESSA: high efficiency stimulated emission source

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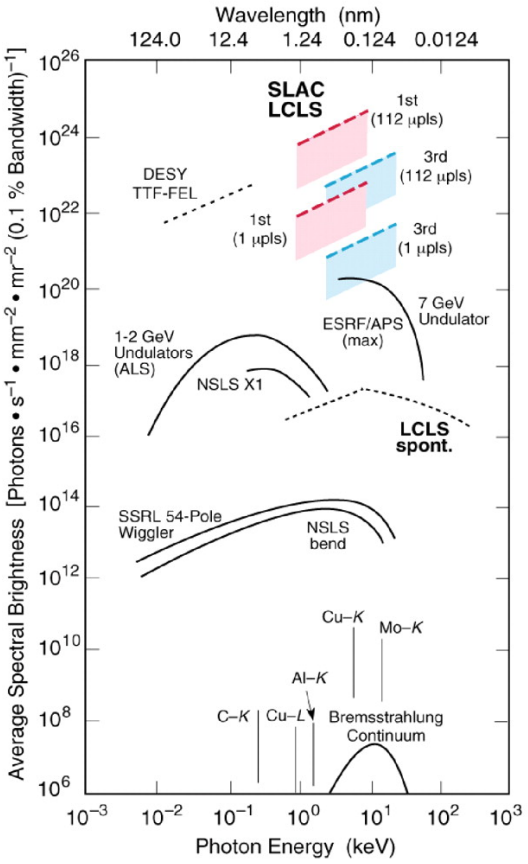
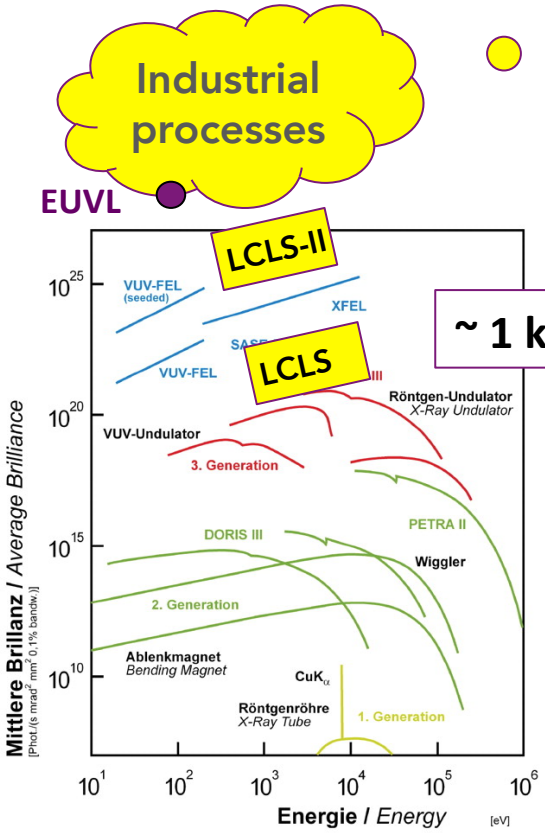
The challenge of industrial XFEL

- X-ray FELs surpassed synchrotron light sources in peak and average power, but are not at the industrial level yet





~ 100,000 kW-hr/year

> 2,000 kW-hr/year

~ 1 kW-hr/year

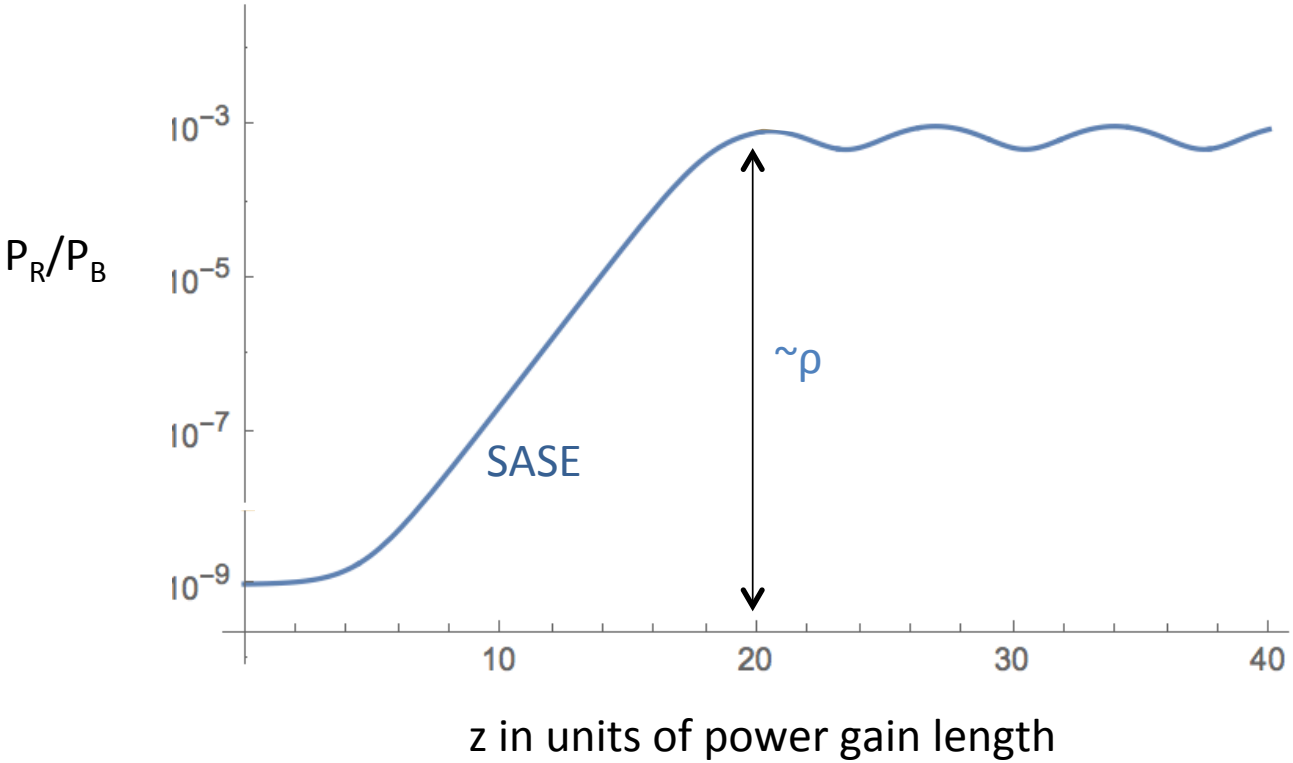
Need to further reduce cost per photon by 2 orders of magnitude compare to state-of-the-art

Outline

- **FEL efficiency limit**
- **TESSA concept**
- **TESSA at EUV**
- **Plans for TESSA experimental validation**

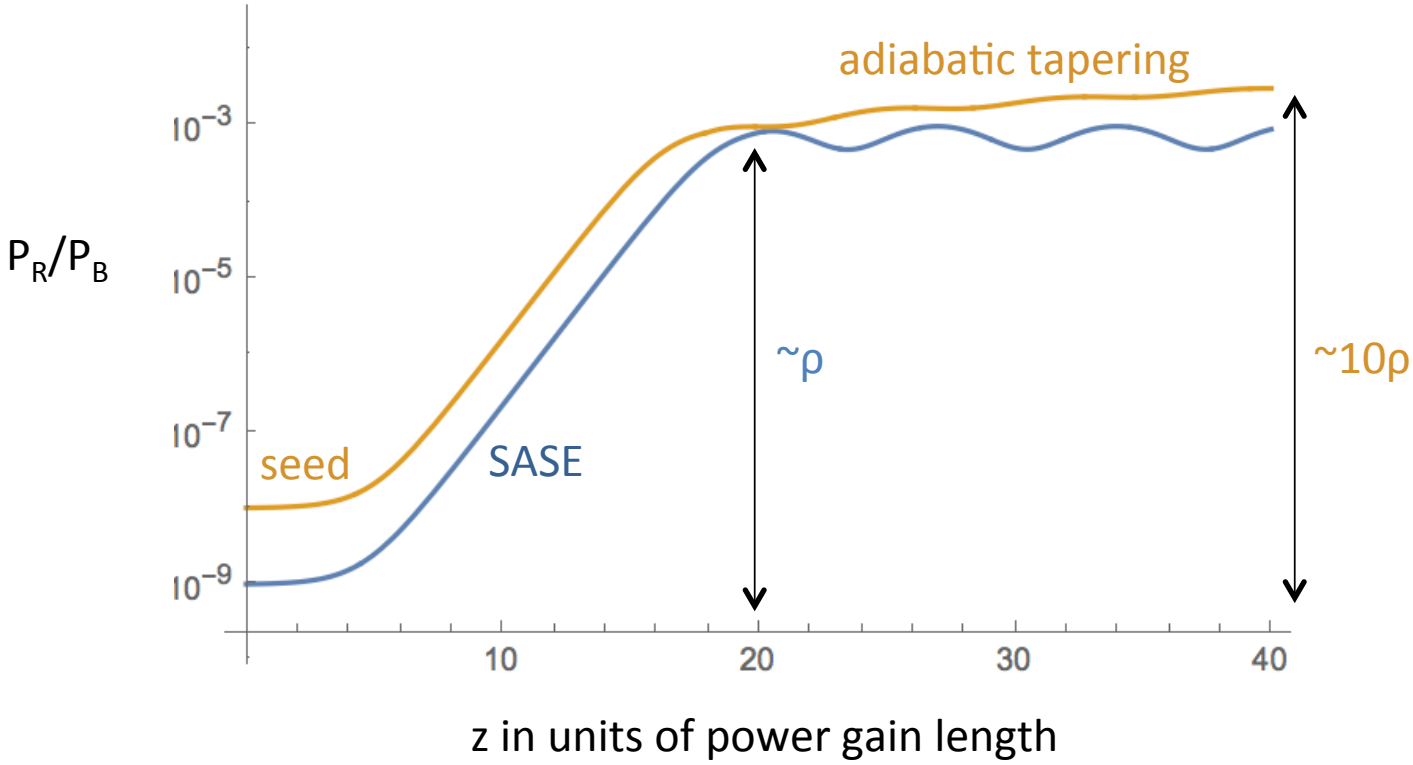
FEL efficiency

- A conventional single pass FEL energy efficiency is limited by Pierce parameter (~ 10^{-3} for EUV and soft X-rays)



Tapered FEL efficiency

- Adiabatic taper keeps beam in resonance beyond saturation
- The power gain is limited by longitudinal dynamics and a practical undulator length



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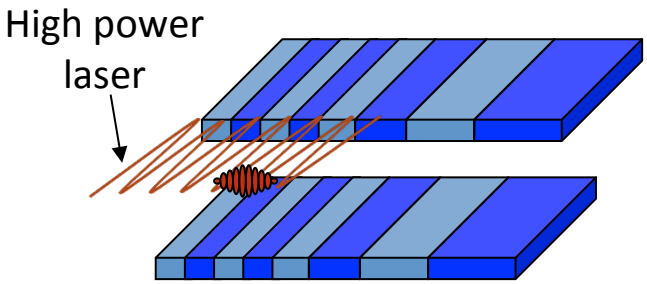
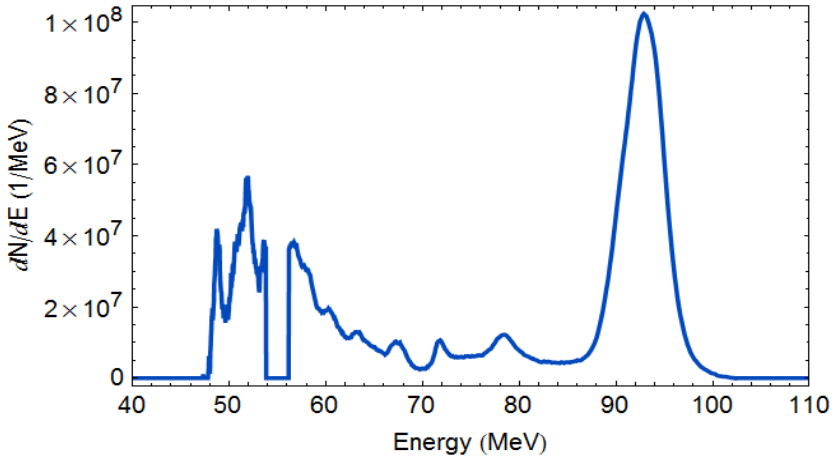
Lessons from Inverse FEL

- FEL beam-laser energy exchange is usually < 1 MeV/m
- IFEL demonstrated energy exchange rate ~ 100 MeV/m
- Design studies indicate possibility of 1 GeV/m
- ***Can we run IFEL in reverse?***



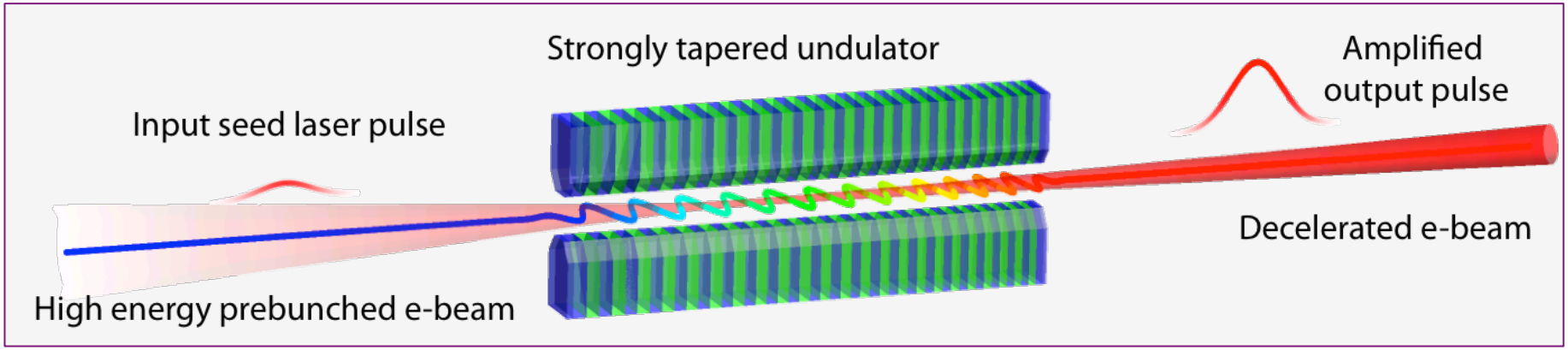
In an IFEL the electron beam absorbs energy from a radiation field.



UCLA results from RUBICON experiments
J. Duris et al, *Nature Comm*. **5**, 4928, 2014

TESSA

- Inverse IFEL = ~~FEL~~ TESSA (**T**apering **E**nhanced **S**timulated **S**uperradiant **A**mplification)
- E-beam rapid deceleration → laser amplification
- Requires seed pulse of high intensity (larger than P_{SAT})
- E-beam can be prebunched, or it can be bunched in the first few undulator periods

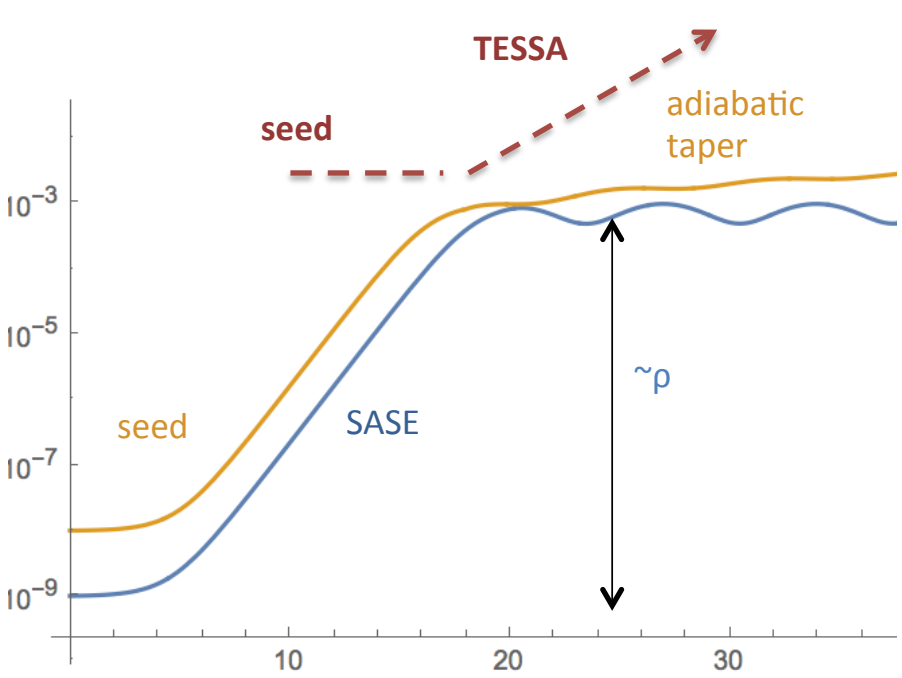


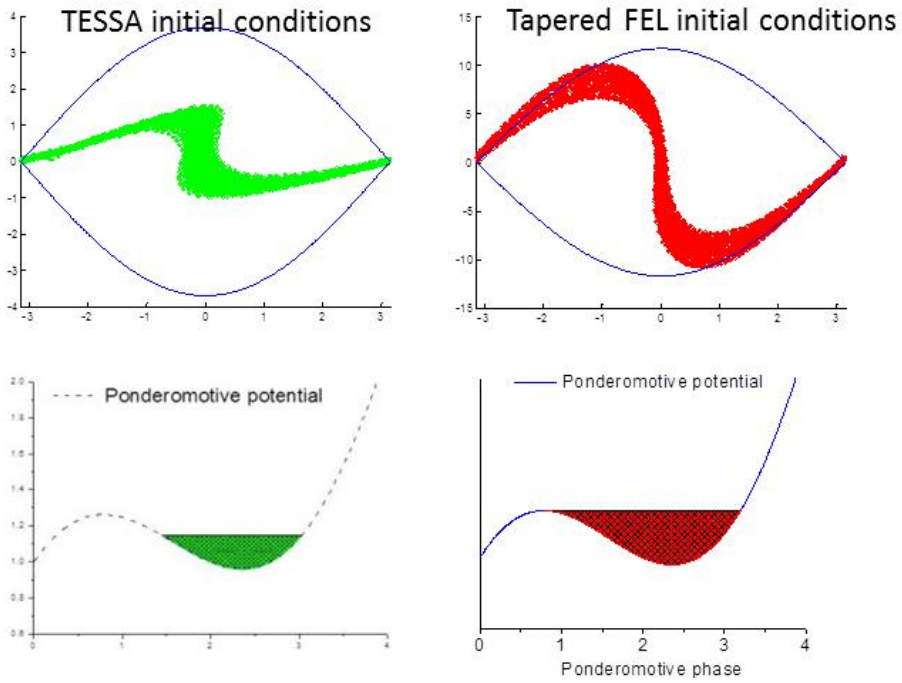
TESSA physics

- **High gain regime** (maximum efficiency):
  - Field changes every period
  - GIT optimization is necessary to find the best solution for undulator period length and field strength
  - 3D effects and initial conditions are important
- **Low gain regime** (some special cases, like an oscillator configuration):
  - Field changes per pass are insignificant, but beam decelerates rapidly
  - Simplified optimization procedure
  - Stimulated emission, less sensitive to beam properties

TESSA vs. tapered FEL

- TESSA operates at much stronger field intensity:
  - **stimulated emission** vs. spontaneous (order of magnitude higher rate of beam-laser energy exchange)
  - 100% beam capture despite very aggressive tapering





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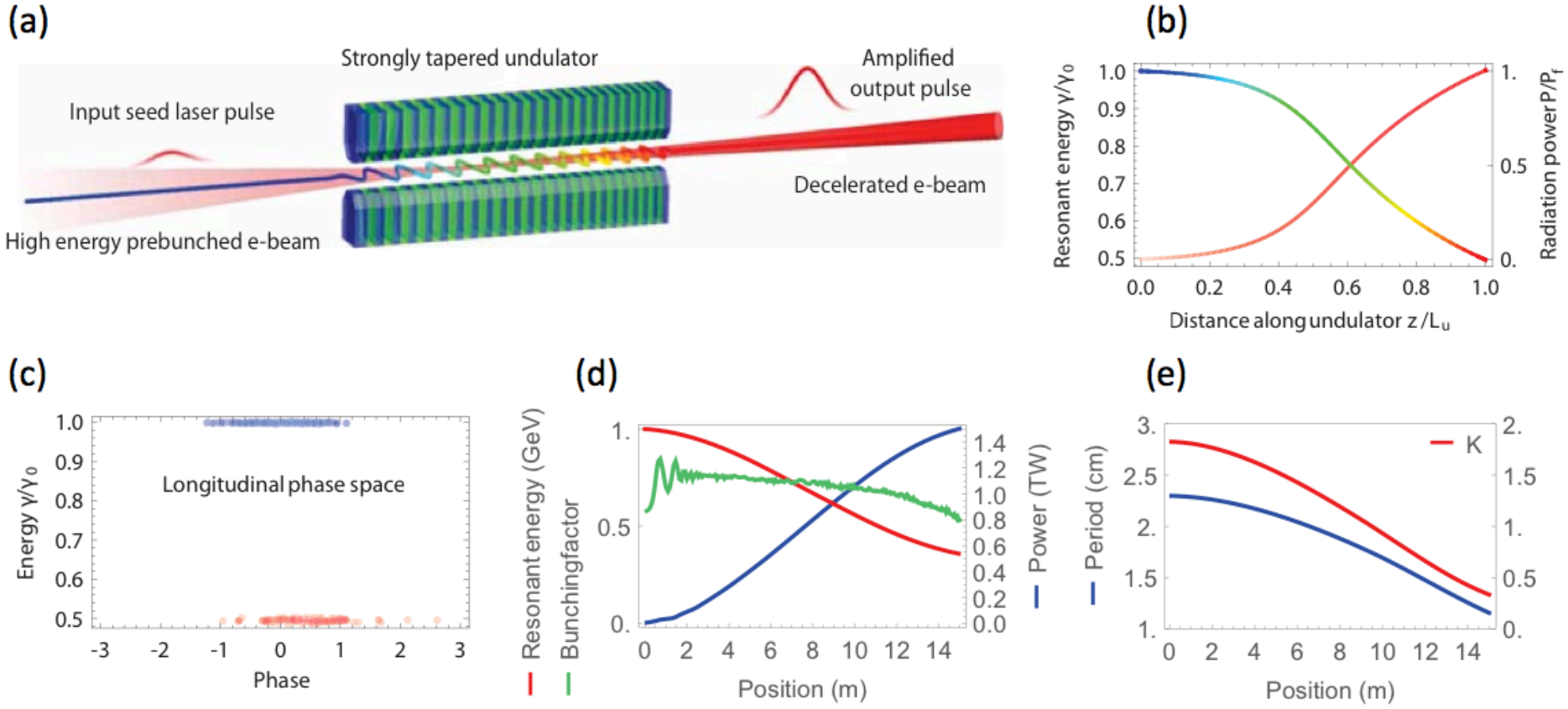
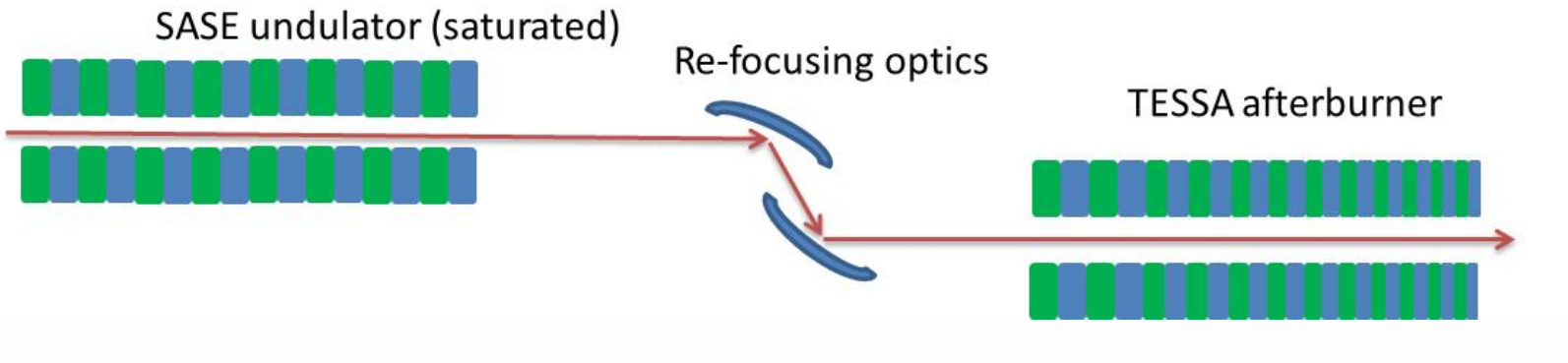
GIT simulations at 13.5 nm

- Refocusing SASE to recreate high intensity condition
- With 3 kA beam achieved **50% efficiency** in 15 meters !

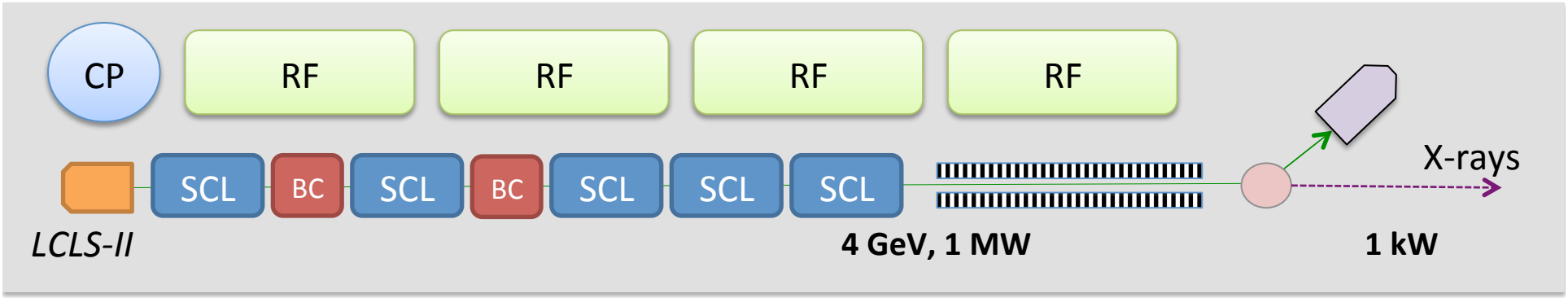


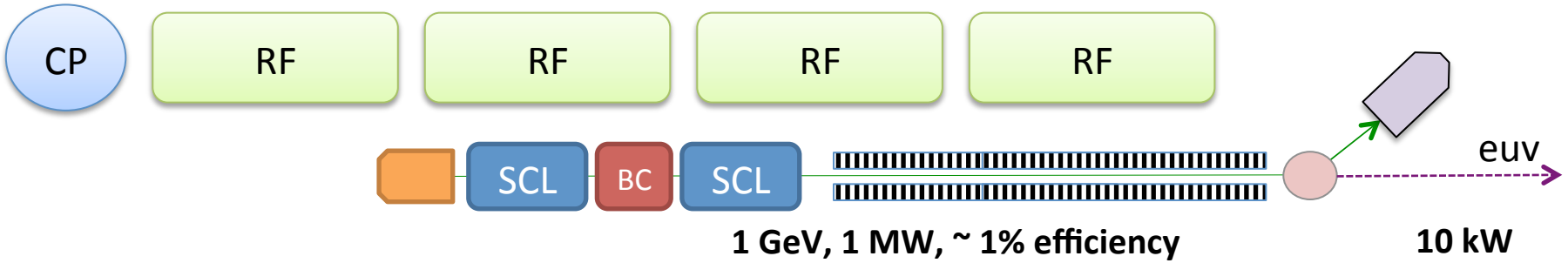
TESSA seeding

- Requires intensity higher than saturation intensity of an FEL
- In visible spectrum TESSA can be seeded by an optical laser
- At EUV GW-class external sources do not exist, so one can use a conventional undulator and at saturation refocus the power to seed TESSA afterburner.



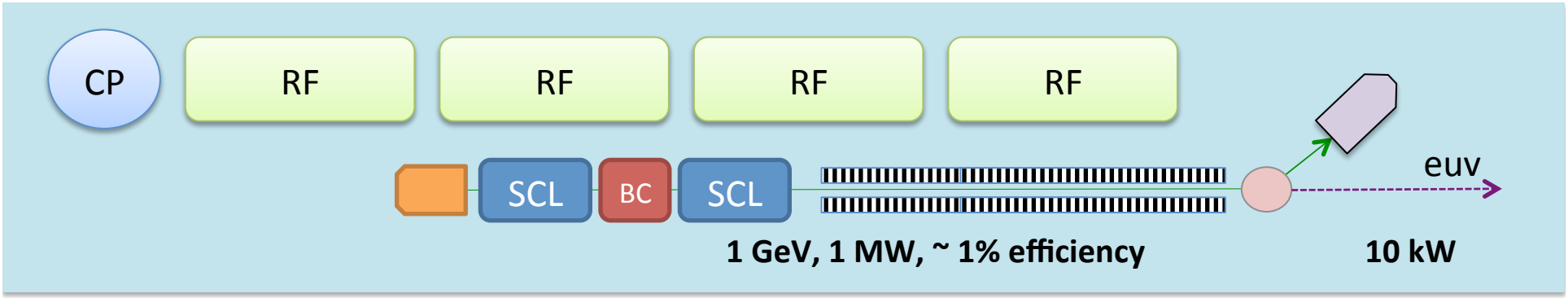
Path to EUV FEL: (step 1) straight shooter

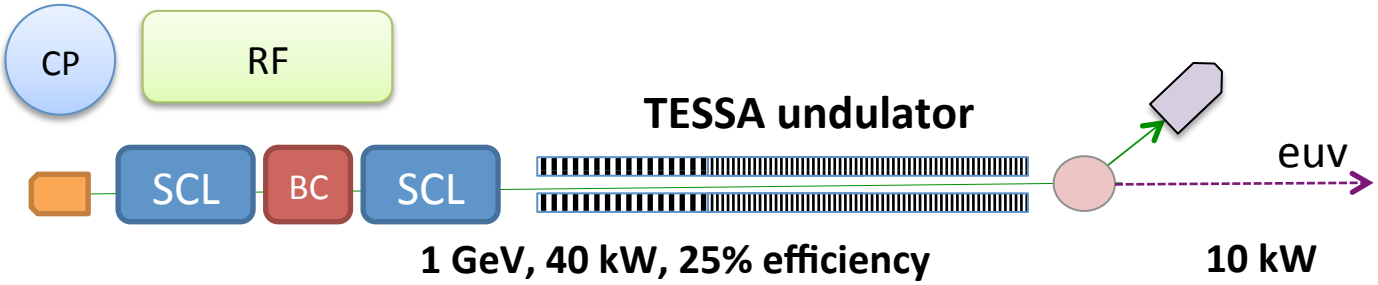




- Extension of LCLS-II technology
- Requires high efficiency (>1%) XFEL development
- Same cost as ERL but less risk

Path to EUV FEL: (step 2) TESSA





- Upgrade to straight shooter, once TESSA is demonstrated
- Requires proof of concept demonstration
- Major reduction in cost and engineering risk

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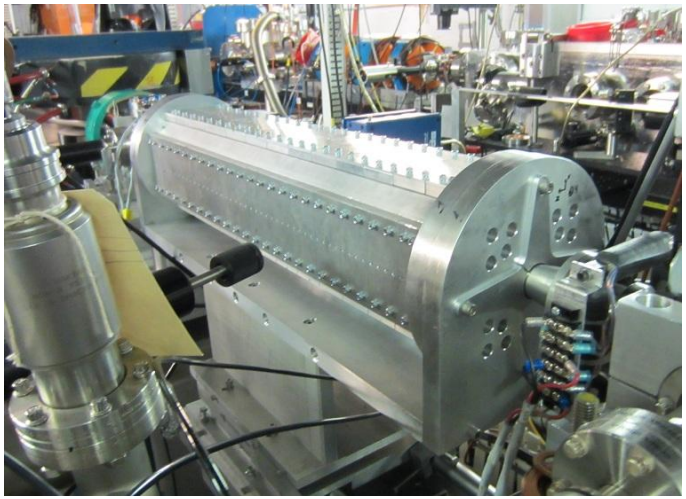
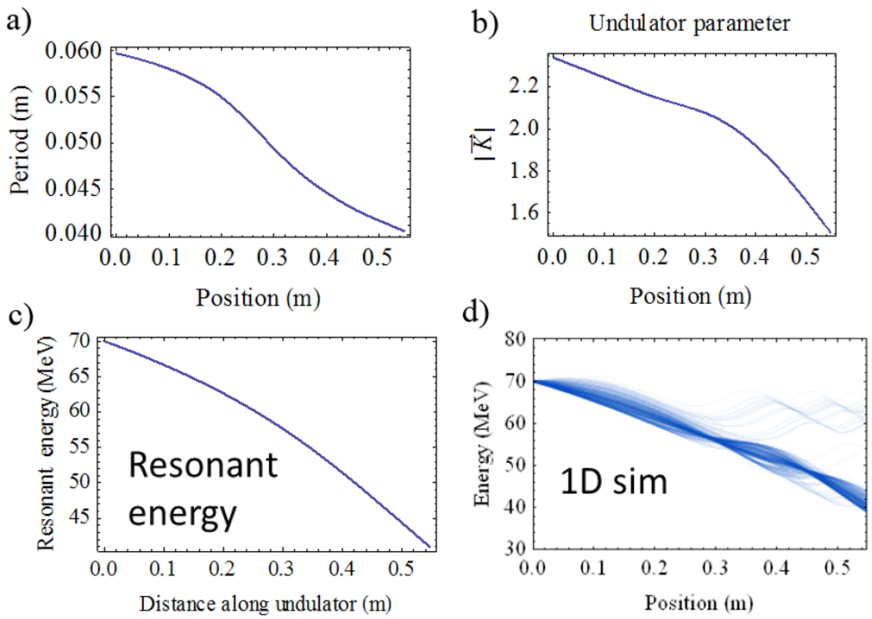
- Use RUBICON IFEL in reverse (ATF)
- Experiment is planned in Q3'15
- Limitation: deceleration only (low gain), amplification is insignificant

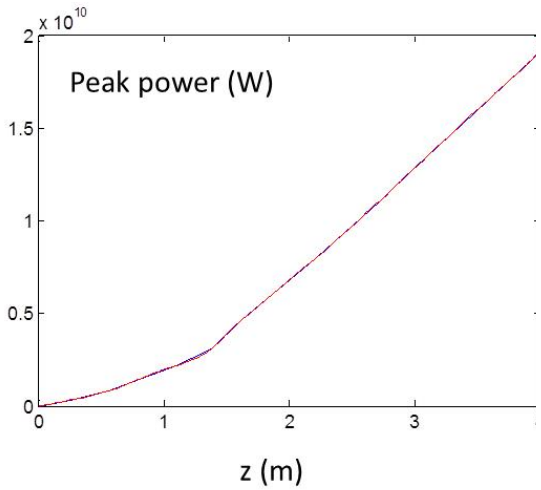


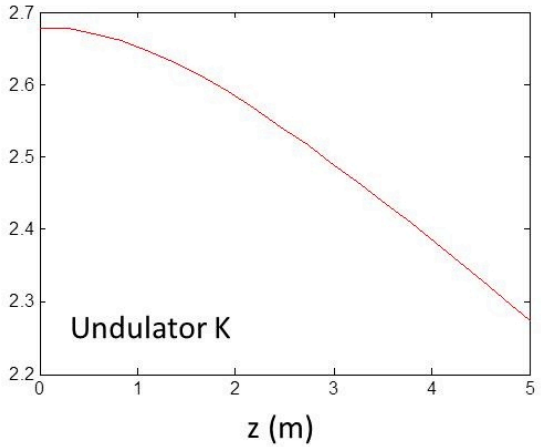
Parameter	Value
E-beam energy	70 to 42 MeV
E-beam current	1 kA
Laser focal intensity	4 TW/cm^2
Laser wavelength	10.3 μm
Rayleigh range	30 cm
Laser waist	1.0 mm
Input peak power	100 GW
Output peak power	130 GW

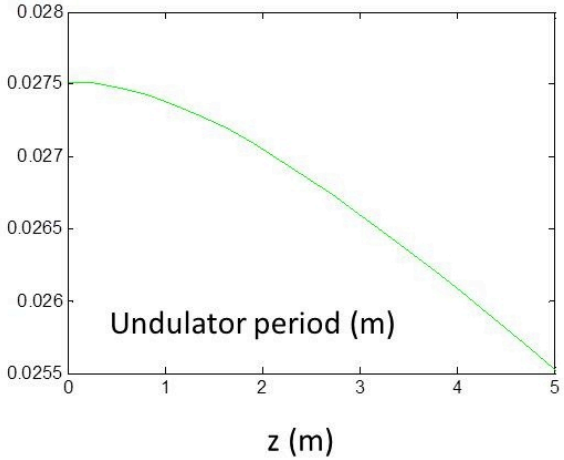


High gain TESSA Amplifier

- To demonstrate orders of magnitude amplification (high gain), we plan to use 266 nm laser as a seed, focused to a small spot size
- Preliminary studies indicate over 3 orders of magnitude TESSA amplification in 4-5 meters undulator at 266 nm, with energy extraction in the range of 10-30 % depending on the e-beam parameters.







Conclusions

- TESSA is a novel concept to achieve over an order of magnitude improvement to FEL efficiency
- TESSA is supported by thorough numerical simulations (GIT) and indirect evidence from IFEL experiments (UCLA)
- The experimental plan to demonstrate TESSA is underway (low gain –> high gain –> RA TESSA –> 13.5 nm?)
- TESSA development and implementation could have a strong impact on industrial source development for EUV lithography (can be a direct upgrade to straight shooter topology).

- Thank you!